Troubleshooting Radiated Emissions –A Practical Approach

Kenneth Wyatt

Abstract

Because time-to-market and budget factors often drive many of today's high-tech designs, electromagnetic compatibility (EMC) issues often surface at the last moment in the design cycle, potentially delaying product introductions. Very often, simple pre-compliance measurements and techniques can identify issues early when the cost of implementation is substantially lower and design improvements may be made with less impact on schedules. This paper describes a number of simple techniques and tools useful in characterizing the radiated emissions (RE) of a design at various stages of development and will better prepare products for a successful radiated emission qualification.

Keywords

radiated emission, field probe, troubleshooting kit

Introduction

There are usually five key threats that comprise most electromagnetic compatibility (EMC) problems—radiated emissions, ESD, susceptibility to RF fields, power disturbances and internal crosstalk. Of these, radiated emissions (RE) can be the most difficult EMC test for a product to pass. Because emissions limits are established worldwide, products that don't meet the limits may not be placed on the market. The best way to achieve this is through proper product design, but often these design techniques are not taught in universities, nor are these techniques fully understood by many experienced engineers. In many cases, EMC is considered as 'black magic' and many products must be tested repeatedly through a system of "trial and error", in order to finally pass.

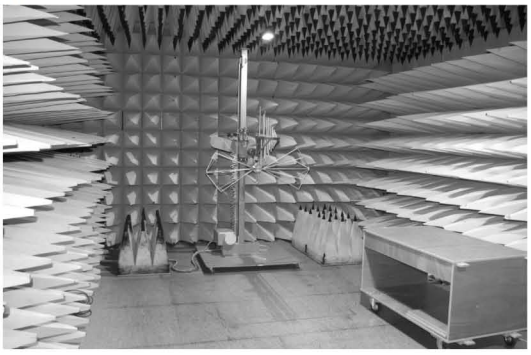

Figure 1: Photo of a typical 3m radiated emission test chamber.

This is unfortunate, because the emissions a product may produce is easily understood if the designer considers that it's the high-frequency currents in circuit loops that tend to broadcast these emissions. These circuit loops may be in the form of printed circuit traces (differential-mode currents) or cables connecting two subsystems (common-mode currents). There may also be combinations of these phenomenon. The circuit and system design level of a product usually falls within the domain of the electronic engineer. The other consideration is the shielding properties of the product, which typically falls within the domain of the mechanical engineer. Ideally, these to must work together as a team to address the whole product in order to be successful in addressing EMC.

Background Theory

In order to better understand RE and how to troubleshoot your product, we must review how harmonics are created and then understand differential-mode (DM) and common-mode (CM) currents and how they get generated. General design techniques are mentioned but specific design practices are a subject for another paper.

A periodic square wave (Figure 2) may actually be represented by a series of more basic signals called "basis functions". Assuming the rise and fall times of the square

wave are straight up and down, an infinite number of harmonically-related basis functions or sine waves are required. Digital circuitry today uses rise and fall times of sub-nanoseconds, which can generate harmonics of several hundreds to thousands of MHz.

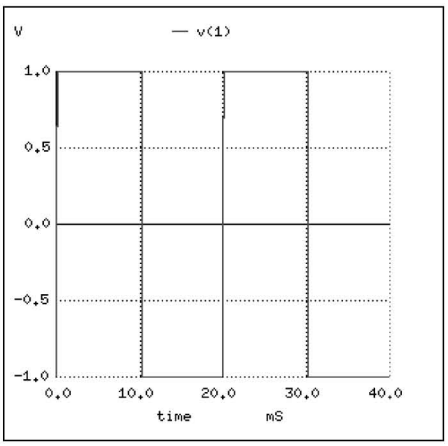

Figure 2: A periodic square wave digital signal

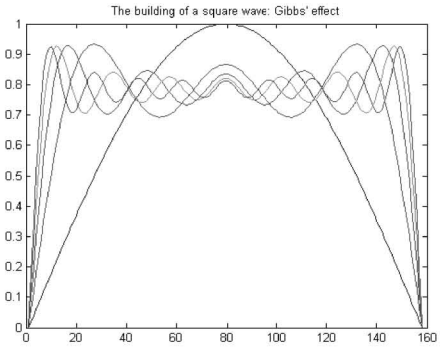

Figure 3: A representation of the square wave is comprised of a linear combination of basis functions, or sine waves. Image courtesy of MathWorks.

Differential-mode (DM) currents are caused by digital signals (and their harmonics) traveling through circuit loops. The larger the loop, the stronger the fundamental and harmonic emissions. We want to minimize the area of any circuit loops through use of ground planes (typically by use of multi-layer circuit boards). For low-cost products, multi-layer boards may not be feasible, so other design techniques must be used to minimize these loops.

Let's consider a simple circuit loop with a square-wave source and resistive load. The fundamental (signal) current, plus all the related harmonic currents, will circulate around the loop as shown. Let's assume we have a receiving antenna 3m away from this circuit loop. These currents are really phasors. When the phasor produced by the far wire is added to the phasor produced by the near wire, the result is the difference in phasor magnitudes, which produce a small resultant phasor and relatively low emission as shown in Figure 4. The area of the loop, the current levels and harmonic frequencies, dictates how much radiation will be produced.

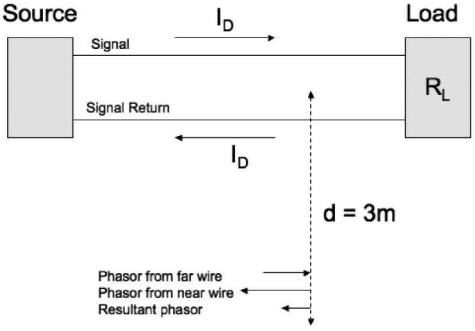

Figure 4: Differential-mode currents in a circuit loop. The source is a digital signal (with harmonics) and we'll assume a resistive load. Because the phasor current in the far wire is opposite the phasor current in the near wire, the resultant phasor is relatively small compared to that produced by common-mode current phasors. However, reducing the loop area is very important in limiting radiated emissions.

The equation for calculating the emission level in volts/meter for a DM signal flowing in a loop is shown below in Equation 1.

$$\left|\hat{E}_{D,\max}\right| = 1.316\times10^{-14}\frac{\left|\hat{I}_D\right| f^2 Ls}{d}$$

Equation 1: Field level (V/m) due to DM current, where f = frequency (Hz), L = length of the wires (m), s = spacing between wires (m) and d = the measurement distance (typically 3m or 10m).

So, how do we minimize the emissions from a DM circuit loop? Note that the area of the loop is $L \cdot s$. First, we must realize that I_D is likely fixed by the design. Likewise, frequency f, is probably fixed. However, length of the loop L, and distance s, may be reduced. In other words, the area of the loop may be decreased to reduce emissions. This is an important point to keep in mind during circuit layout. Placing a crystal oscillator (one common source of harmonics and resulting emissions) close to the circuitry that requires the clock signal is a good design practice. Likewise, the use of multi-layer boards with full ground planes serves to reduce the loop area substantially.

Now, let's consider common-mode (CM) currents and how they are generated, because it is not intuitive as to how current may travel the same direction through both the signal and signal-return wires in a system. Referring to Figure 5, note that due to finite impedance in any

grounding system (including circuit board grounds), there will be a voltage difference between any two points within that ground. This is denoted by V_{GND1} and V_{GND2} in the figure. This difference in potential will drive CM currents through common cabling or circuit traces between circuits or sub-systems. These CM currents may be generated on circuit boards or within sub-systems inside product enclosures. Because the current phasors are additive, the resulting radiated phasor may be quite large compared to those generated by DM currents. Therefore, CM currents tend to be more of an issue than DM currents.

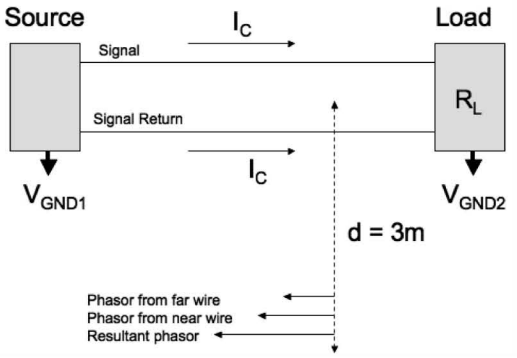

Figure 5: Common-mode currents in a circuit loop. The source is a digital signal (with harmonics) and we'll assume a resistive load. Because the phasor current in the far wire is in the same direction as the phasor current in the near wire, the resultant phasor is relatively large compared to that produced by differential-mode current phasors. In this case, lowering the harmonic content (by slowing the digital rise/fall-times) or diverting/blocking the CM current is very important in limiting radiated emissions.

The equation for calculating the emission level in volts/meter for a CM signal is shown below in Equation 2.

$$\left|\hat{E}_{C,\max}\right| = 1.257\times10^{-6}\,\frac{\left|\hat{I}_C\right| fL}{d}$$

Equation 2: Field level (V/m) due to CM current, where f = frequency (Hz), L = length of the wires (m) and d = the measurement distance (typically 3m or 10m).

Note that the exponent is now -6, rather than -14 – a much larger number; thus, the emissions from CM currents are typically much higher than that from DM currents. So, how do we minimize the emissions from a CM circuit loop First, we must realize that frequency, *f* and the length of the cabling, *L* is likely fixed by the design. However, I_C, which is an undesirable signal, may be reduced by either using a lower-impedance ground, or by blocking (with a ferrite choke or with CM filters) or by diverting through proper mechanical design. This is an important point to keep in mind during system design.

The solution to most EMC problems is to **Control The Path of Current!**

Troubleshooting Philosophy–Radiated Emissions

In troubleshooting any radiated emission problem, it's useful to think of the problem in the form of a 'source-path-receptor' model. See Figure 6 below.

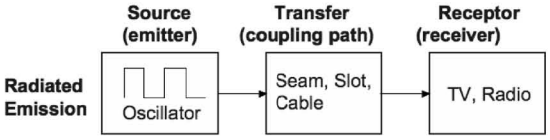

Figure 6: Source–Path–Receptor model. Typically, the source of radiated emissions is a high-frequency crystal oscillator or other high-frequency, fast-edged, high-current signal. ASICs, FPGAs and A/D or D/A converters may also generate these high-frequency harmonics. The 'path' is the coupling mechanism, or the means by which the high-frequency energy is being radiated. The 'receptor', in most cases is the EMI receiver at the test site with specified emission limits.

By using various probes, it should be possible to identify the source or sources. Once the sources are identified, the path or coupling mechanism must be identified and fixed. What's difficult is that there may be multiple sources and coupling mechanisms to identify and fix, before passing results are achieved. In addition, if a fix is improperly installed, the emission can actually get worse! That's probably why the field of EMC is considered so "mysterious".

By using a structured approach, the troubleshooting phase should go smoothly. Generally, you'll want to diagnose the issues first then try various fixes. Leave these fixes installed as you continue the troubleshooting process. If you set up an antenna and EMI receiver or spectrum analyzer a fixed distance away (1 to 3m) from where you're troubleshooting you can monitor your results real-time.

IDENTIFY THE SOURCES–The first step should always be to identify the likely sources. If you're failing at 300MHz or 500 MHz, for example, are these the third or fifth harmonics of a 100 MHz clock oscillator? How about the memory clocking? Generally memory address and data busses are fairly random. The exception would be the A0 or D0 line, which is clocking at a relatively non-random rate. What about clock lines to ASICs or FPGAs? If you have multiple crystal oscillators, which could be the cause

of a particular harmonic, spraying "freeze spray" on one then the other—can often identify the offending oscillator.

FREQUENCY—The frequency is key to any radiated emission problem. As a quick rule of thumb, the higher the frequency, the more likely the coupling path is radiated. The lower the frequency, the more likely the path is conducted. In fact the common break frequency is 30 MHz. Below that, we measure conducted emissions (CE)—above that we measure RE. If your product uses a high-frequency crystal oscillator with fast edge speeds, the harmonic content can be estimated with the formula in Equation 3.

$$f = \frac{1}{\Pi \times t_r}$$

Equation 3: Maximal RE frequency estimate, where f = EMI frequency (Hz) and t_r = risetime (s).

For example, with 1ns logic, the harmonic content may be centered around 300 MHz. Another rule of thumb is that for frequencies below about 300 MHz, the problem is most likely due to common-mode emissions from cables and above that; the problem is most likely radiation from slots or seams in the metal chassis or circuit board radiation.

DIMENSIONS—The dimensions of physical structures are also an important factor in troubleshooting an emissions problem. Recall that the wavelength (m) of a resonant wire at frequency *f*, in free space is:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{f}$$

Equation 4: Wavelength of a wire, where c = speed of light in m/s and f = frequency in Hz.

The dimensions in physical structures, like circuit boards must be reduced by the velocity factor of the board material (example, 4.7 for FR4 circuit boards). However, typical cables, such as USB or video) are approximately 1m long and can be considered as being in free space. Wires or slots may resonate strongly at multiples of a quarter wavelength. For example, a 1m long cable has a full-wave resonance of 300MHz, but may also radiate strongly at 150MHz and 75MHz. Slots or seams of 8 to 15cm may resonate in the area of 500 MHz to 800 MHz. As a general rule of thumb, radiating cables or chassis slots of 1/20th wavelength or greater, start to become significant coupling paths for RE.

PROBES—There are a variety of useful probes that may be used to troubleshoot RE problems: E-field, H-field and current probes. The E-field and H-field probes are easily made in the lab. All are available from several manufacturers[1]. An E-field probe may be made by extending the center conductor about 0.5 cm from a section of semi-rigid coax or high-quality flexible coax; then attaching a coax connector to the other end. Shorting of the probe to circuit traces may be avoided by wrapping insulating tape around the end. A useful H-field probe may be fashioned by looping the center conductor around and soldering it to the shield to form a small loop of 0.5cm to 5 cm in diameter (the larger the loop), the more sensitivity. A better H-field probe design uses semi-rigid coax to form the loop (see examples in Figure 7). These probes are then connected to the input of an EMI receiver or spectrum analyzer to display the harmonics as the probe is brought into close contact with the circuit traces or chassis slots. Depending on the diameter of your H-field probe, you may need to use a broadband preamplifier between the probe and analyzer[2].

Figure 7: Examples of commercial E-field and H-field probes from Beehive Electronics.

Figure 8: Examples of home made H-field probes.

1 Probe manufacturers include Fischer Custom Communications (www.fischercc.com), Beehive Electronics (www.beehive-electronics.com) or Teseq (www.teseq.com).

2 I made my own broadband preamp using a MiniCircuits model ZX60-3018G-S, which covers 20 MHz to 3000 MHz at 18-23 dB gain and 2.7 dB noise figure. It sells for USD 50.

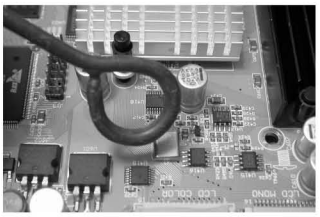

Figure 9a: Use of simple H-field probes to locate emission sources.

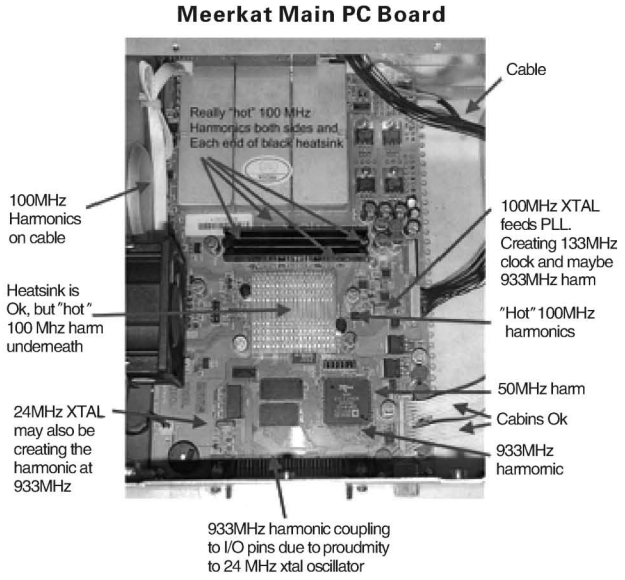
Meerkat Main PC Board
Really "hot" 100 MHz Harmonics both sides and Each end of black heatsink
Cable
100MHz Harmonics on cable
100MHz XTAL feeds PLL. Creating 133MHz clock and maybe 933MHz harm
Heatsink is Ok, but "hot" 100 Mhz harm undemeath
"Hot" 100MHz harmonics
50MHz harm
Cabins Ok
24MHz XTAL may also be creating the harmonic at 933MHz
933MHz harmonic
933MHz harmonic coupling to I/O pins due to proudmity to 24 MHz xtal oscillator

Figure 9b: I map out all the potential sources; documenting them on a photograph of the circuit board.

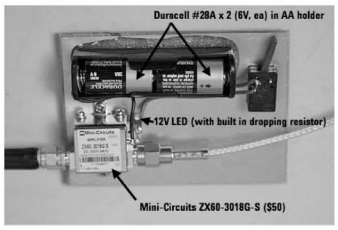

Figure 10: I made my own broadband preamp using a Mini-Circuits model ZX60-3018G-S. It is powered it with two 6V Duracell #28A batteries, which fit in a standard 'AA' battery holder. The amplifier covers 20 to 3000 MHz at 18–23 dB gain and is used to boost the probe signals.

TROUBLESHOOTING STEPS—Generally, once you are finished mapping out your sources, you should start with the lower harmonics and work upwards. Often, lower-frequency sources will cause significant high-frequency harmonics, depending upon the rise time. By fixing the low-frequency source, you'll often resolve high-frequency harmonics, as well. Next, check cables and then the enclosure.

CABLES—Check your cables first, as they are often the worst offenders. Moving a 'hot' cable will alter the RE levels. I usually unplug all cables; then try plugging each one in individually to find all that are radiating.Remember that there may be more than one bad cable! Snapping a ferrite choke around the base of the cable will probably help as an interim fix. I've found that most cable emissions are very likely due to poor grounding at the I/O connector.

Cable currents may also be measured directly versus frequency with a current probe[3]. Examples are shown in Figure 11.

Figure11: Examples of commercial current probes.

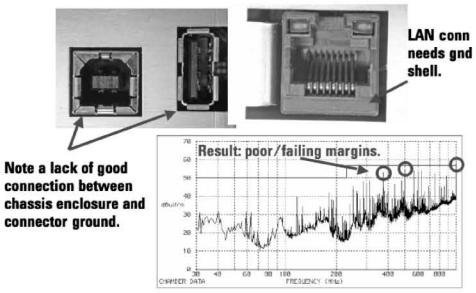
LAN conn needs gnd shell.
Note a lack of good connection between chassis enclosure and connector ground.
Result: poor/failing margins.

Figure 12: Poor I/O connector grounding to the chassis allows the cable to radiate and usually fail the RE test. A lack of solid ground can allow CM currents generated inside the product to flow out the I/O cable and radiate sually causing RE failures. The included graph shows poor margins to the CISPR 11 Class A 3m RE limit (for ISM products, in this case). ITE products, such as PCs and printers have a limit 10 dB lower.

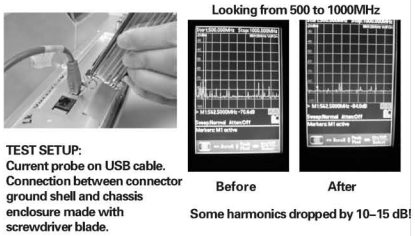
Looking from 500 to 1000MHz
TEST SETUP:
Current probe on USB cable.
Connection between connector ground shell and chassis enclosure made with screwdriver blade.
Before
After
Some harmonics dropped by 10–15 dB!

Figure 13: Cables should be tested individually. Here, I have a current probe clamped around the cable under test and am monitoring the harmonics with a simple hand-held spectrum analyzer[4]. As I ground the connector shell to the chassis with the screwdriver blade, the harmonics are reduced 10 to 15 dB!

3 Commercial current probes are available from Fischer Custom Communications (www.fischercc.com), Teseq (www.teseq.com) or Solar Electronics (www.solar-emc.com).

4 The handheld spectrum analyzer being used for the cable test is made by Thurlby Thander Instruments (www.tti-test.com). It sells for approximately USD 1500 and covers 150 kHz to 1 GHz.

It is possible to actually predict whether a particular cable will pass or fail by measuring the CM current at the offending frequency, solving for IC (Figure 14 and Equation 5 below) and plugging this into Equation 2 to solve for the field level in V/m. The length of the cable is L and the offending harmonic frequency is f. Use a test distance of either 3 or 10m to predict the outcome at those test distances.

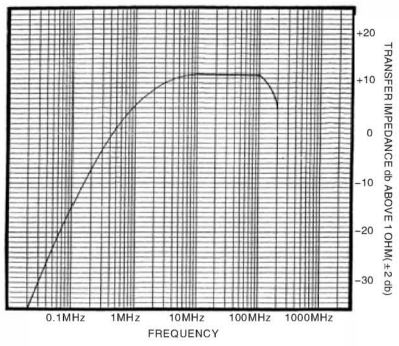

Figure 14: Transfer impedance (Z_T) graph of a typical current probe (courtesy of Fischer Custom Communications). The x-axis is frequency, while the y-axis is dBΩ. Use this to calculate the value of IC, given the measured voltage at the probe terminals (V_{dBuV}) and Z_T.

$$\left|\hat{I}_C\right|_{dB\mu A} = \left|\hat{V}\right|_{dB\mu V} - \left|Z_T\right|_{dB\Omega}$$

Equation 5: Calculation of I_C given the measured V and Z_T (from Figure 14). Next, plug I_C into Equation 2 to calculate the predicted E-field emission level in V/m. Converting this to dBuV/m will indicate a pass or fail due to the cable being measured.

SLOTS & SEAMS—Once the cables and associated I/O connectors are addressed, it's time to probe for radiation leakage through slots or seams in the chassis. Remember, that the length of the slot or seam is important. Any seam with leakage whose effective length is longer than 1/20th of a wavelength at the harmonic of concern has the potential to be an effective radiator. For example, a slot of 2.5cm can just start radiating harmonics at 1000 MHz. I use a permanent marking pen to record the areas of leakage and frequencies of concern from every seam/slot on the chassis.

Once these are marked, I'll carefully cover over all the openings with copper tape and re-measure the RE levels. Keeping an eye on the RE levels, I'll start removing the tape piece-by-piece to determine which slots or seams are actually causing problems. Often, just a few slots or seams are causing the most problems. Once the leakages are identified, you can determine the appropriate fixes with your mechanical engineer.

It's also possible to use a differential probe and high-bandwidth oscilloscope to measure any voltage differences between pieces of sheet metal on the chassis enclosure. If any voltage is measured, it indicates a poor connection and potential leakage. Figure 13 shows how to place one tip on each side of the joint. Ideally, the voltage should measure zero.

Figure 15: Use of a differential probe and high-frequency oscilloscope or spectrum analyzer to measure the potential difference across suspected gaps in the seams of a product enclosure. Ideally, this voltage should measure zero.

TROUBLESHOOTING KIT—For speedy troubleshooting and analysis, I've assembled an EMC troubleshooting kit into a portable case, which can be wheeled right to an engineer's workbench. Major contents include a small spectrum analyzer, a broadband preamplifier, small antennas, various probes and other accessories. Other useful items to include into your troubleshooting kit include ferrite chokes, aluminum foil, copper tape, power line filters, signal filters and various values of resistors and capacitors. Figure 15 shows an overall view of the contents.

Figure16: Contents of the special EMC troubleshooting kit I've assembled. I can probe for various RE problems, as well as test for ESD and radiated immunity. Performing these tests early in the design cycle, results in a greater chance of passing the required EMC product qualification tests.

Summary

In order to pass required EMC tests for radiated emissions, it is necessary to understand the basic concepts of current flow through loops, as well as differential- and common-mode currents and how they're generated. Troubleshooting an existing design is simply the process of identifying the likely sources, determining the coupling mechanisms through probing, and applying temporary fixes. Once these fixes have been applied and the product passes, then the electronic and mechanical engineers may determine the most cost-effective solutions. Obviously, troubleshooting or characterizing products early in the design cycle *Continued on Page50*

If there is only one type in an application unit, the type of sample should be delivered. Representative samples should be chosen and delivered if certification application of a series of products is within the same application unit.

d) Relative standards (Refer to Table from page 44 to page 47)

e) Factory inspection

On-site examination on factories is an important precondition for enterprises to obtain CESI certification for the first time, as well as mantaining effectiveness of certificate. Usually, the examination includes initial examination and at least one time reinspection per year, as to the latter, the enterprises would be informed or not informed beforehand. Content of factory examination includes examination on certified products and requirements on quality system of the factory, which involve factory's: responsibility and resource, documents and records, procurement and incoming goods examination, manufacture process control and process examination, routine examination and confirmation examination, examination on instruments and equipments, control on unqualified products, internal quality examination, coincidence of products and packaging, removal and deposition of products, totally in ten aspects. Those requirements would ensure that batch manufactured certificated products can comply with requirement of CESI certification standard, and consist with certificated type of sample.

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are preferred in order to reduce overall implementation costs.

Kenneth Wyatt–*Sr. EMC Engineer, Wyatt Technical Services, LLC, holds degrees in biology and electronic engineering and has worked as a senior EMC engineer for Hewlett-Packard and Agilent Technologies for 21 years. He also worked as a product development engineer for 10 years at various aerospace firms on projects ranging from DC-DC power converters to RF and microwave systems for shipboard and space systems. A prolific author and presenter, he has written or presented topics including RF amplifier design, RF network analysis software, EMC design of products and use of harmonic comb generators for predicting shielding effectiveness. He has been published in magazines such as, RF Design, EMC Design & Test, Electronic Design, Microwave Journal, HP Journal and several others.*

Kenneth is a senior member of the IEEE and a long time member of the EMC Society where he serves as their official photographer. He is also a member of the dB Society and is a licensed amateur radio operator.

His comprehensive yet practical EMC design, measurement and troubleshooting seminars have been presented across the U.S., Europe and Asia. He currently resides in Colorado and may be contacted at ken@emc-seminars.com. His Web site is: www.emc-seminars.com.

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Safety and EMC Testing Center of Electronics Industry (SEC) is legally owned by China Electronics Standardization Institute (shortened as CESI). SEC is a government approved Testing Lab (approved by the former Ministry of Electronic Industry of the P. R. C.) specialized in safety and EMC testing of electronic products, aiming at supporting the government on quality supervision. SEC is an independent and non-profit testing body.

SEC was authorized by Certification and Accreditation Administration of the People's Republic of China (CNCA) to evaluate safety and EMC performance of products. CESI mark is one of several marks designated by CNCA, which can be accepted by 3C certification. The components having acquired CESI certification don't need to be tested again during 3C certification process of equipments. That also means the manufacturers having obtained CESI marks on their products have passed the certification of national-level certificate authority. As a result, value-added of products will undoubtedly increase. As a matter of fact, certificated components can be used by electronic equipment manufacturers more preferably; consequently, it will lead to the increase of product sales volume and bring more benefits to the manufacturers.